APPLICATION OF AUTOMATIC CODE GENERATION FOR RAPID AND EFFICIENT MOTOR CONTROL DEVELOPMENT

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Hybrid Vehicle Motor Controls Overview

Requirements dictate fast algorithm execution

- Torque, speed, voltage and fault reaction modes
  - 1000+ Hz fundamental frequency
  - 500+ Hz current regulator bandwidth
  - 10 kHz PWM rates for DC voltage ripple
- 80 – 100 uSec control loops are common
Software Development Process

General Approach

- Responsibilities
  - Systems: Analyze, derive and specify
  - Software: Implement
  - Software/Systems/Validation: Verify

- Time consuming and error prone
  - Requirements formation, implementation and verification are too dispersed
  - Decoupling of domain knowledge from implementation
Automatic Code Generation

Benefits

• Linking of simulation, code development and testing
  ▪ Common in 5 – 10 mSec task rates
  ▪ Improves testability.
• Implementation responsibility transitions to domain experts
• Potential for time savings
  ▪ Faster verification of implementation
  ▪ Production hardware can be used for design and detailed problem solving

Challenges

• Creating and maintaining easily understood environment and models
• Identifying preferred implementations
Develop automatic code generation process for time critical tasks

- Requirements focused
  - To support Automotive SPICE
- Directly apply system expertise to implementation
  - Create path for high level simulation models to software
- Shorten time between design, implementation and verification steps
  - Reduce development time
- Create easy to understand implementations that can be shared among teams
- Closely match hand-code throughput efficiency
Process: Requirements Derivation / Partitioning Phase

High level design

• Verify overall requirements are met
• Establish derived requirements
  - Architecture
  - System partitioning
  - Modes
  - Sample rates / control bandwidths

Diagram:
- HYBRID CONTROL MODULE
- Operating Mode:
  \( T_e^* / \omega_r^* \)
- Reference Frame Transformation:
  \( I_{qa}, I_{qb}, I_{qc}, U_{SA}, U_{SB}, U_{SC}, L_{SA}, L_{SB}, L_{SC} \)
- Resolver Signal Processing
  \( \theta_r, \omega_r \)
- 3-Phase Bridge
  \( V_{dc} \)
- TORQUE / SPEED REGULATOR
  \( I_{qs}, I_{qs}^*, I_{ds}, I_{ds}^* \)
- CURRENT REGULATOR
- MODULATOR
  \( I_{as}, I_{bs}, I_{cs}, S_{AL}, S_{BL}, S_{CL} \)
Process: Implementation Phase

Functional Modules

- Testable requirements
  - Inputs / outputs
  - Functionality
  - Execution rate / order
- Model development
  - Best practices
- Documentation
  - Model / requirements are not sufficient
- Test vectors
  - Simulation
  - Requirements verification
Process: Implementation Phase (Modelling)

Simulation tools offer numerous options for implementation

- Not all approaches will code with equal efficiency
  - Tools have optimization settings
- Consistency of implementation among modules is important for ‘readability’
  - Key for sharing among teams
- Peer review process is important to ensure efficient code
  - Systems: Implementation meets requirements
  - Software: Optimization and problem resolution
    - Detailed review of code
    - Identification of best practices
Process: Implementation Phase (Example 1)

Inefficient Model / Code:

```c
real32_t rtb_Gain3;
real32_t rtb_Add2;
rtb_Add2 = Vds_Stat - Vgs_Stat;
T_1_Prime = Vgs_Stat - Vds_Stat;
rtb_Gain3 = 2.0F * Vds_Stat;
switch (Sector_Num) {
  case 3:
    T_1_Prime = rtb_Gain3;
    break;
  case 2:
    T_1_Prime = rtb_Add2;
    break;
  case 4:
    T_1_Prime = rtb_Gain3;
    break;
  case 5:
    T_1_Prime = rtb_Add2;
    break;
  case 1:
    break;
}
```

Efficient Model / Code:

```c
switch (Sector_Num) {
  case 3:
    T_1_Prime = 2.0F * Vds_Stat;
    break;
  case 2:
    T_1_Prime = Vds_Stat - Vgs_Stat;
    break;
  case 4:
    T_1_Prime = 2.0F * Vds_Stat;
    break;
  case 5:
    T_1_Prime = Vds_Stat - Vgs_Stat;
    break;
  case 1:
    T_1_Prime = Vgs_Stat - Vds_Stat;
    break;
  default:
    T_1_Prime = Vgs_Stat - Vds_Stat;
    break;
}
```
Process: Implementation Phase (Example 2)

Inefficient Embedded MATLAB code:

```matlab
floor_index = uint32(unfloor_index);
```

Generated code:

```c
/* =================================== */
/* '<S3>:1:46' */
tmp = unfloor_index;
if ((unfloor_index < 8.388608E+6F) && (unfloor_index > -8.388608E+6F)) {
    tmp = (unfloor_index < 0.0F) ? ceilf(unfloor_index - 0.5F) : floorf
        (unfloor_index + 0.5F);
}
floor_index = (uint32_T)tmp;
```
Process: Implementation Phase (Example 2)

Inefficient Embedded MATLAB code:

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    (unfloor_index + 0.5F);
}

floor_index = (uint32_T)tmp;
```
Process: Implementation Phase (Example 2)

Efficient Embedded MATLAB Code:

Hand-coded CustomFunction.h:

```c
#ifndef CustomFunction_H
#define CustomFunction_H

#include "rtwtypes.h"

#define SingleToInteger32(u) ( (int32_T) u )
```

Generated code:

```c
/* '<S3>:1:46' */

floor_index = SingleToInteger32(unfloor_index);
```
Process: Verification Phase

Test to verify requirements are met

• Module test vectors
  ▪ Verify functionality
    • Inputs / internal variables / outputs

• Full model test vectors
  ▪ Simulation environment
  ▪ Hardware in the loop
    • Correct compiler
    • Simulate virtual load in processor or test bench
Evaluation of Process

Verified auto generated software was dynamometer tested to evaluate performance

- Comparison was made to mature hand-code
- Equivalent motor control functionality
- Slight penalty in 100 uSec task throughput
  - 1.54 uSec

<table>
<thead>
<tr>
<th>Task / Module</th>
<th>Throughput (uSec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
</tr>
<tr>
<td>Current Magnitude and Phase Process</td>
<td>1.42</td>
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<tr>
<td>ABC to dq0 Frame Transformation</td>
<td>0.76</td>
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<tr>
<td>Resolver Harmonic Learn</td>
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<tr>
<td>Angle Position Determination</td>
<td>0.93</td>
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<tr>
<td>PI-Current Regulator</td>
<td>7.62</td>
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<tr>
<td>Torque Mode</td>
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<tr>
<td>dq0 Rotating to Stationary Frame Transformation</td>
<td>0.94</td>
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<tr>
<td>Complete 100 uSec Task</td>
<td>65.37</td>
</tr>
</tbody>
</table>
Summary

Structured automatic code generation can be applied to time critical tasks

• A process is required to ensure efficient implementations
• New roles
  ▪ Software: responsible for auto-coding environment, determining best practices, peer reviewing implementations and detailed problem solving
  ▪ System: responsible for forming requirements, creating implementations that demonstrably meet requirements (test vectors) and following identified best practices
• Requirements and models are not sufficient to document implementation
• Automatic code generation should be viewed as a tool to link simulation, implementation and verification testing
  ▪ Concurrent activities speed the software development process
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